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Author(s): Hull, Lawrence M.
Gray, George T. III
Faulkner, James R.
Briggs, Matthew E.

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Damage in Low Alloy Steel Produced by Sweeping, Interacting Detonation Waves

L Hull¹, G Gray², J Faulkner³, M Briggs⁴
Los Alamos National Laboratory, USA

¹lh@lanl.gov
²rusty@lanl.gov
³jrf@lanl.gov
⁴briggs@lanl.gov

Abstract. Detonation waves that sweep along the surface of a metal plate induce reduced pressure and enhanced shear, relative to the same detonation at normal incidence. Detonation waves at intermediate obliquity impress intermediate combined stress states. Release waves from the free surfaces may enter into play and contribute to the damage. Initiation of explosive at discrete points produces strong pressure, density, and velocity gradients in the gaseous explosive products in areas where the waves collide, are impressed in an adjacent metal, causing similar stress gradients within the metal that often leading to intense damage. In this work, we investigate damage generated in AISI 4130 steel by the combined effects of oblique drive and interacting detonation waves. The experimental data consist of multipoint velocimetry points probing the free surface in regions loaded by interacting detonation waves and regions between the interactions. Metallography on recovered plate records the plastic flow and damage correlated with the velocimetry data. Spall is indicated in most regions, but not some, and the alpha-epsilon stress-induced phase transformation appears in most regions, but not all. Correlations of the observed physical effects with incident wave obliquity and transverse position relative to the wave interactions are discussed.

1. Introduction

Interacting (colliding) detonation waves produce strong gradients in the explosive products pressure, density, velocities, in fact all of the variables of the flow. In the configuration studied here, these conditions drive a 4130 steel plate at variable angles of obliquity and eventually sweep along the plate tangentially. The normal stresses in the explosive are from a true gaseous pressure, and the shearing stresses in the explosive products are viscous, while those in the metal are related to the strength. Exceeding the strength of the material typically results in damage, such as spall. Spall damage may be generated relatively globally by the overall dimensions of the explosive, metal, and any confining parts, or may be local and directly related to the detonation wave interactions. Any material effect may be influenced by the $\alpha \rightarrow \epsilon$ phase transition that is observed in this work with 4130, and reported by Franz [1] with 4340 steel, and expected in other low-alloy steels. Further, even under conditions in which micro-scale material damage is not produced, the detonation wave interactions can induce a perturbed global, periodic motion of the plate. Generally, such periodic motion may either grow into unstable motion, such as Rayleigh-Taylor instability, or it may damp out without becoming unstable. The stability of the motion is determined by the perturbation wavelength, by the magnitude and direction of continued acceleration, and by the character of the stabilizing forces (e. g. plasticity).

2. Experiment Design

The experiments are defined in Fig. 1. A 25.4 mm thick slab of PBX-9501 is initiated on one edge using PETN boosters initiated by a series of well-separated (8.5 mm) slappers. Each initiation point creates an approximately spherical detonation wave, and each detonation wave interacts with its neighbors, the 4130 plate, and free surfaces. Two configurations were tested, as shown in Fig. 1. In the first experiment (H4309), the 4130 plate was 5mm thick and in the second (H4310), 10 mm thick. The other difference is that an explosive chamfer was added to the second experiment. This chamfer causes the thickness of the explosive driving the plate to vary as a function of distance along the plate

as measured from the start of the explosive, and the angle of interaction between the detonation waves and the plate initially varies differently with distance.

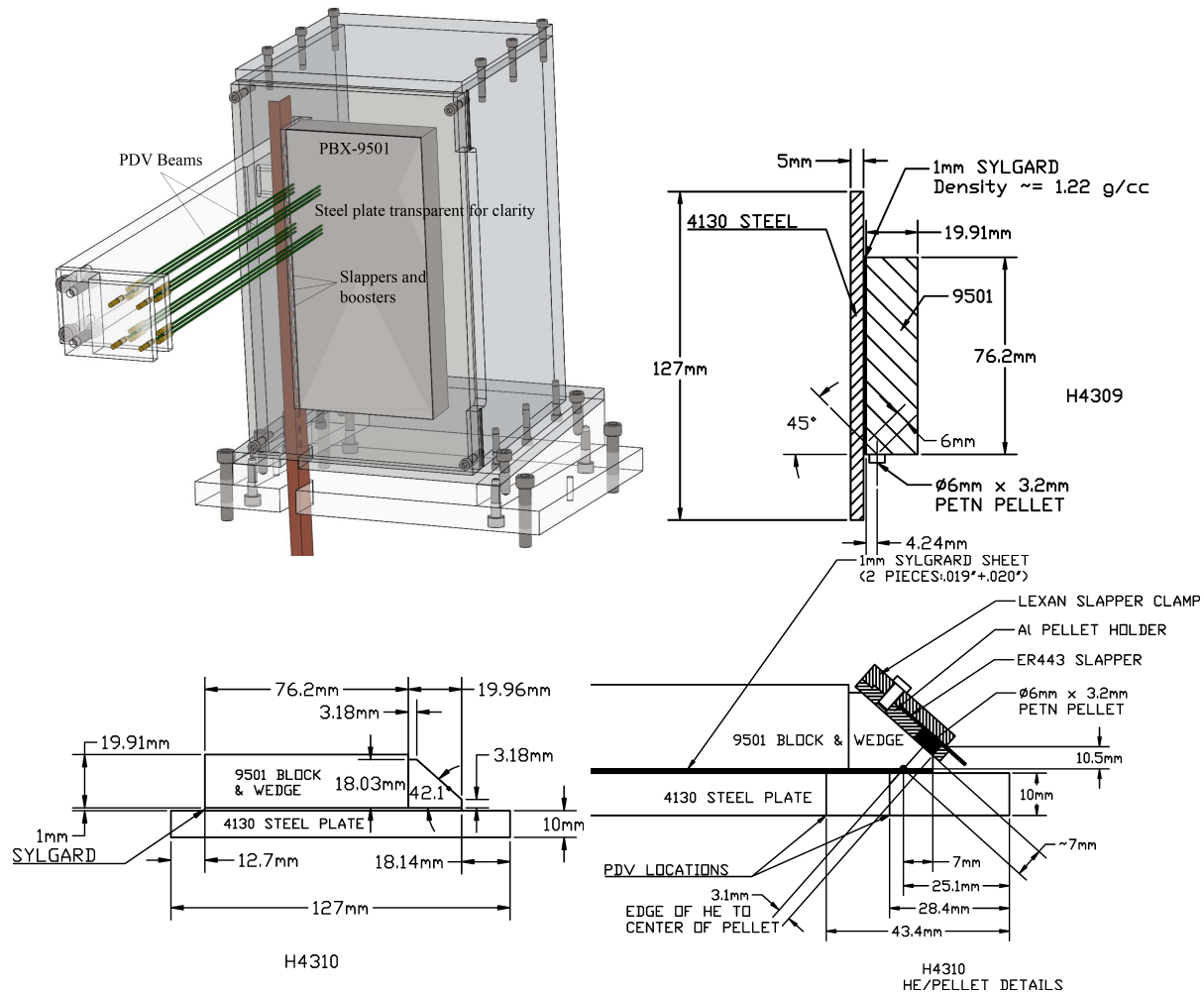


Fig. 1a (top left). An assembly view of H4309 shows the series of slappers, the PDV probes and beams, and the PBX-9501 slab. Fig. 1b (top right). Design drawing of H4309 shows the initiation point specification and dimensions. Fig. 1c (bottom left). Design drawing of H4310 shows the explosive chamfer and overall dimensions. Fig. 1d (bottom right). Design drawing of the chamfered initiation configuration of H4310. The initiation points are spaced 8.5 mm apart and begin 12.5 mm from the lateral edge of the explosive in both experiments.

The diagnostics consist of an x-ray normal to the surface of the plate, an x-ray grazing the plate, and 12 probes of Photon Doppler Velocimetry (PDV). The x-rays reveal thickness variations associated with pronounced damage effects as well as any large debris generation for damage. The PDV probes are arranged in sets of three. Each set probes the velocity of the plate at a point over the line running through the detonator, a point over the line midway between detonators, and a point over a line one quarter of the way between the detonators. There are 4 sets of three. Two sets are close to the detonators, and two sets are further down the plate.

The metal plate was aimed at a polyethylene barrel of water for recovery of the plate. This constitutes a semi-soft recovery technique. The thinner 5 mm plate of H4309 was badly deformed by the

recovery process, but the thicker 10 mm plate of H4310 was not. In either case, the water cooled the plate relatively quickly (~ 5 ms), but some post shot “annealing” likely occurred.

3. Radiographic Results

The normal-view radiographs for both shots are shown in Fig. 2.

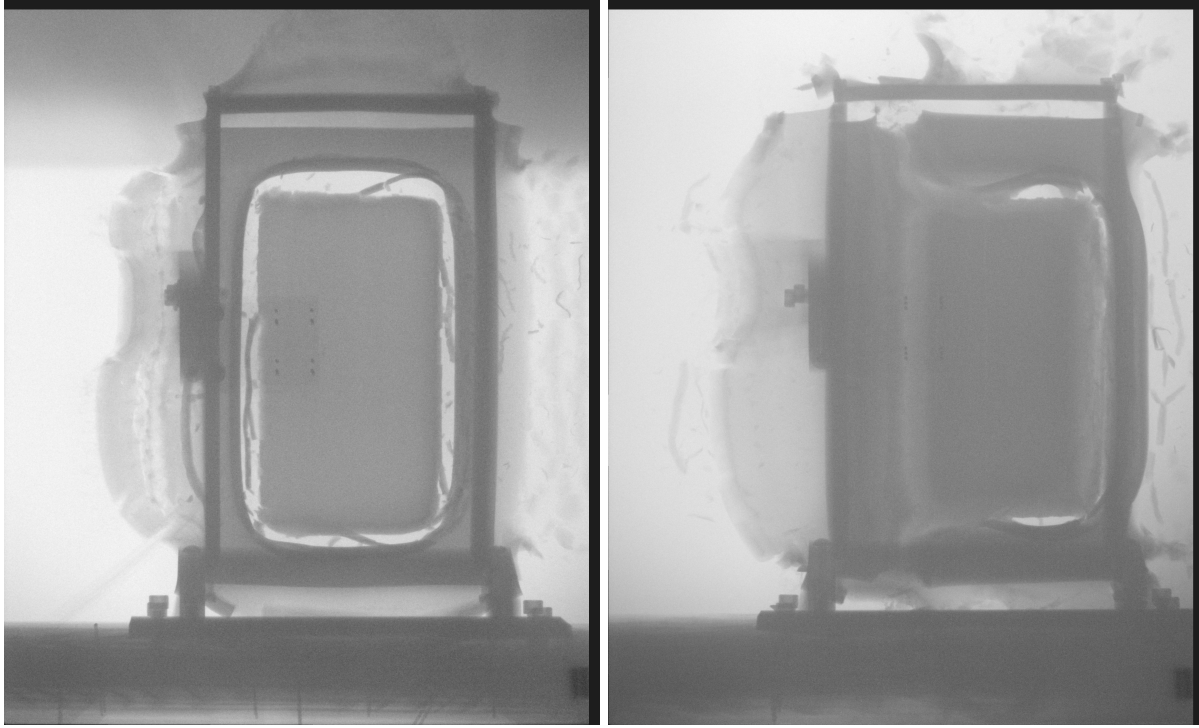


Fig. 2. Normal-view radiographs: Left, H4309, 5-mm 4130 plate. Right H4310 10-mm 4130 plate.

The detonation proceeded from left to right and has completely swept across the plate at the x-ray time of about $50 \mu\text{s}$ for H4309 and $65 \mu\text{s}$ for H4310. Major damage, predominately cutting and spall, are observed in the 4130 plates all around the edges of the explosive. This is the expected behavior near such edges. The edge on the left is the edge where the explosive was initiated. The combined effect of the chamfer, and the thicker plate of H4310, distributes the edge damage over a much broader region near the left, or detonation, edge. The PDV probes are just visible in both radiographs. In H4309, the probes near the detonation edge are close to but not on damaged regions, as assessed by the radiograph, whereas the probes further toward the center of the plate are much farther away. In H4310, the probes near the detonation edge are clearly engulfed by the edge damage region.

4. PDV Results

The shock jump-off velocity records are shown in Fig. 3 for both shots. A break in slope during jump-off characterizes the $\alpha \rightarrow \epsilon$ phase transition, an effect that is easily recognized in several of the traces. Of particular interest is that, of the probes near the detonation edge in H4309, two show the transition, and one does not. All three show the characteristic “pull-back” in velocity followed by a rebound and ringing in velocity associated with spall. Assuming that 1-dimensional theory applies and that the phase stays in the transitioned state leads us to the extraction of 3.5 GPa for α –Fe 4130 and 2.5 GPa for ϵ –Fe 4130 spall stress. The probes further down the plate in H4309 all show the phase transition and no spall signal. The thicker plate of H4310 consistently shows spall at the probe location near the detonation edge without phase transition. Note that the radiography shows that these probes are over

an obviously damaged region. The probes furthest from the detonation edge show the phase transition and a motion that appears to be modified due to the wave interactions but is not spall.

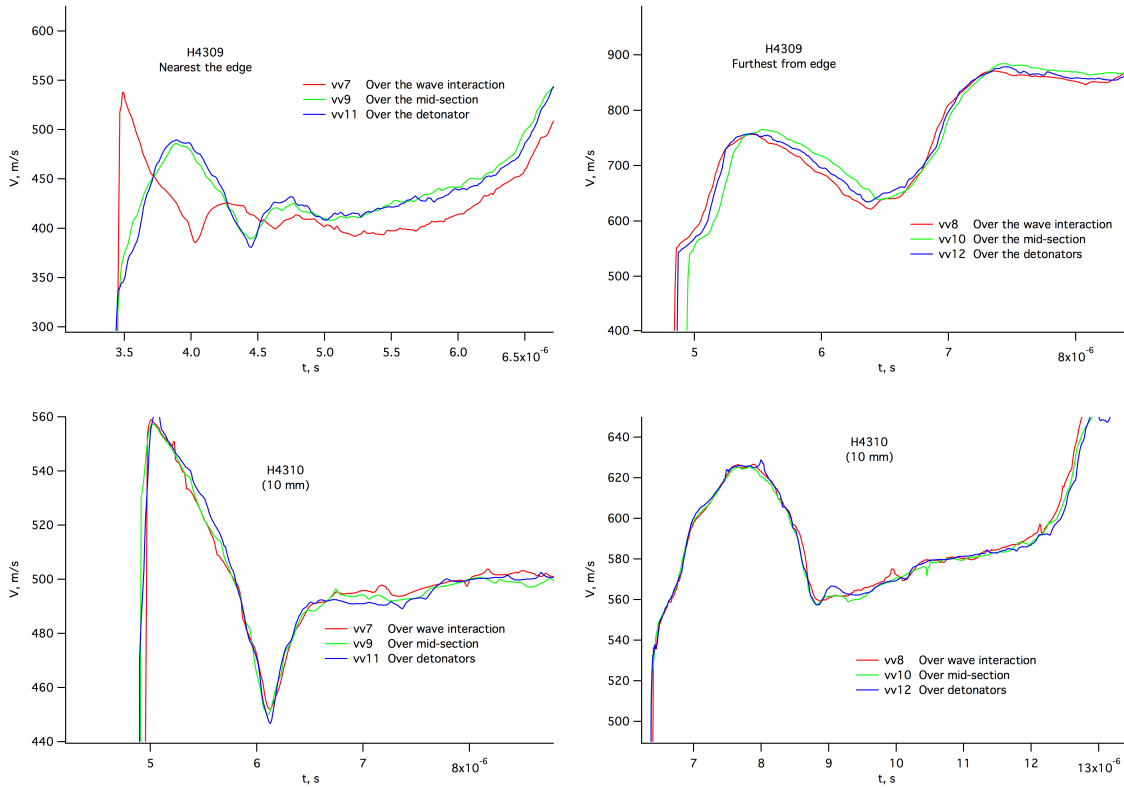


Fig. 3. Jump-off velocity records captured by PDV.

5. Metallographic Results

The recovered 5-mm 4130 plate of H4309 was too deformed by the recovery process to be useful for metallographic analysis. However, the recovered 10-mm plate of H4310 yielded various results of interest, Fig. 4. The free surface is shown in Fig. 4, and is arranged such that the bottom edge in the photo is the detonation edge. Residual perturbations in the free surface profile (vertical ridges), visible in the photograph, have relative amplitude of about $150\ \mu\text{m}$. The three probes furthest from the detonation edge show that the material driven by the wave interactions (midway between the detonators) attains a higher velocity than the material directly under the detonators. The peak to valley velocity difference is on the order of $12\ \text{m/s}$, which is generally above the expected uncertainty in PDV measurements. This velocity difference develops and dissipates in a time interval of about $30\ \mu\text{s}$, presumably due to the effect of plastic flow.

The material under the periodic ridge structure was examined metallographically and by micro-hardness testing, Fig. 5. The explosive/metal interface is heavily twinned, but there are no voids, cracks, shear bands, or other signatures that would characterize a damage mechanism (either material separation or strength degradation). The interaction of the explosive products with the metal causes a shear flow along this interface, and the twins evidently relax or dissipate this shearing motion near the interface and well before the free surface. The periodic wave structure left on the plate is induced by the wave interactions deriving from the discrete point array detonation system. In a pure hydrodynamic flow, these periodic perturbations would be expected to seed instability, but in this experiment the material strength apparently stabilizes the motion. The lack of variation in the micro-hardness data suggests that either some annealing occurred immediately after the shot, or that the plastic flow was not localized on the scale of the measurements.

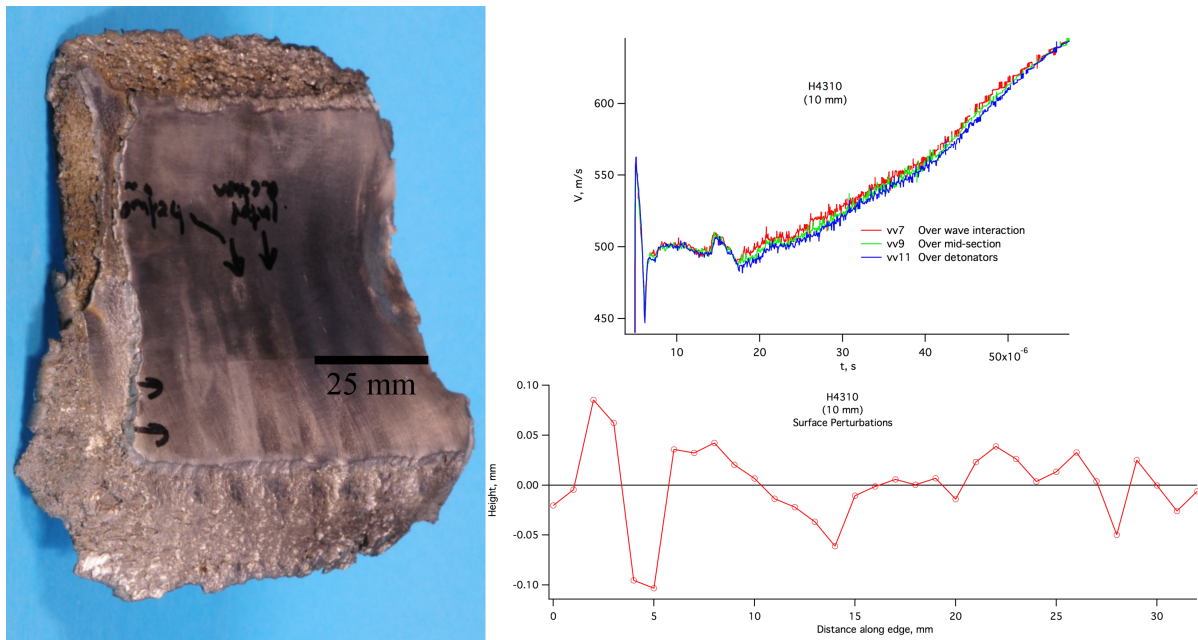


Fig. 4. Photo of recovered plate, the detonators were located along the bottom edge in this view. Also shown are the velocity traces at the location further from the detonation edge (near the scale bar) and the residual surface perturbation amplitude profile, measured optically from the recovered part shown.

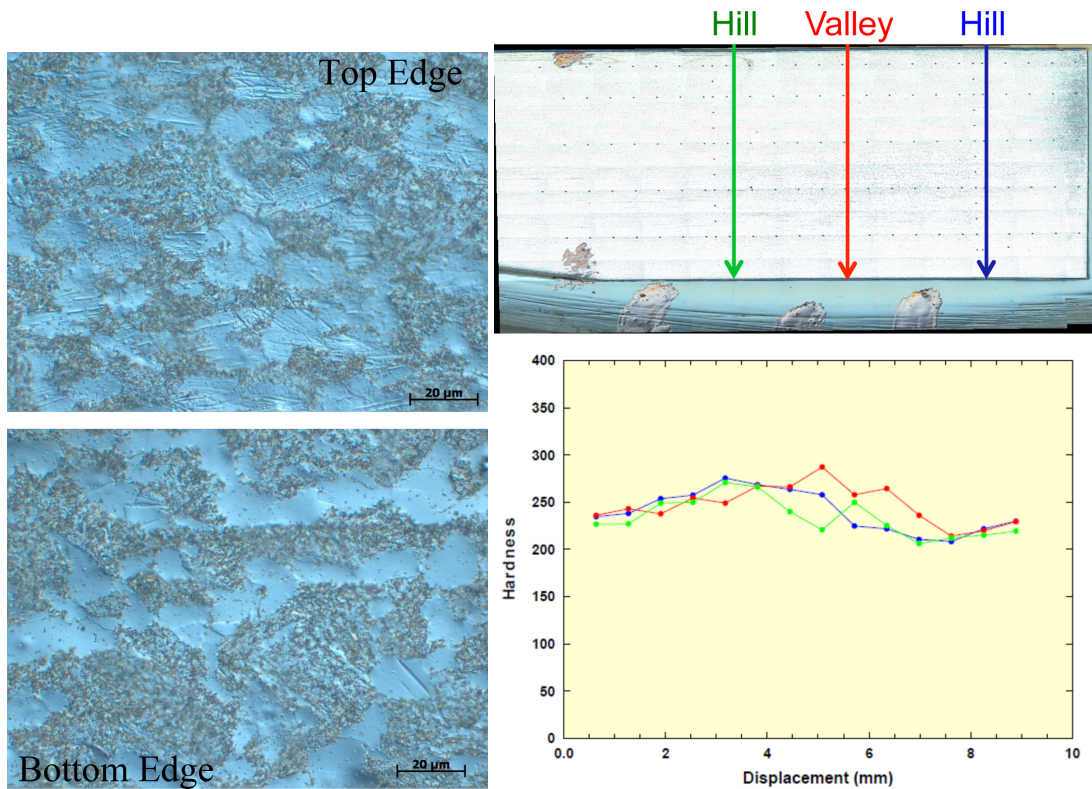


Fig. 5. Left: The top edge, or explosive/metal interface, shows a large twin fraction, whereas the bottom edge does not. Right: The hardness of the recovered plate does not correlate with the hills and valleys of the ridges.

6. Summary

Spall and cutting around the edges of the explosive dominates the damage recorded in these experiments. While this is the expected result, the PDV data show that the $\alpha \rightarrow \epsilon$ phase transition does occur in the damaged region, and apparent spall stress depends on the phase or at least on the occurrence of the phase transition. The data also suggest that the wave interactions caused by the discrete detonation points also influence the appearance of the $\alpha \rightarrow \epsilon$ transition in that one PDV probe over an interaction line did not show the phase transition, while a point displaced laterally by 2.125 mm did show the transition. The wave interactions also caused permanent ripple or ridge-like perturbations in the surface profile with amplitude of about $150 \mu\text{s}$. The PDV data show that these ridges develop a normal velocity difference of about 12 m/s, and that this velocity difference decays in about $30 \mu\text{s}$. Metallographic inspection revealed that no material damage was generated by the perturbations. However, large numbers of twins were generated in regions where high shear occurred. The data are high enough fidelity to be used to validate or adjust detonation, plasticity and damage modeling of 4130 driven by sweeping interacting detonation.

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- [1] Franz R and Robitaille J *The Hugoniot of 4340 Steel RC 54-55*, ARBRL-MR-02951